SIMULATION INVESTIGATIONS OF LANE CHANGE PROCESS WITH AUTOMATIC STEERING SYSTEM

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ABSTRACT

Driver assistance mechatronic systems are standard features of the modern car. This is particularly true of systems that use braking systems (ABS, ESC, etc.). Mechatronic systems directly related to steering mechanisms are very limited, as yet. They apply mainly to support the driver's effort (servo-type systems), and to stabilize the vehicle's trajectory (active steering systems, 4WS systems), in which powering and gearing are speed dependent. Full automation of driving includes, as of now, only the parking maneuver (Parc Assist System), which is implemented at a very low speed - at quasi-static conditions. Full automation of road maneuvers at high speeds (when the car should be treated as a dynamical system) remains difficult and is still open. Automatic control of lane change is a key to automate more complex maneuvers (eg. avoiding, overtaking etc.).
The subject of automation of lane change was undertaken by the authors in the research project on the control of the vehicle with suddenly appearing obstacle. The authors' model of a conceptual control system was presented at the Conference ESV'2015. The aim of extensive simulation studies was: testing of the controller operations, and evaluation of its sensitivity to changes of the vehicle and road parameters. This paper presents unpublished results of these studies.
The lane change controller has a mixed structure. In the open-loop structure it works as a set-point signal generator which generates three variables (signals) determining the lane change maneuver: a set-point input signal of steering system angle, and two set-point output signals describing vehicle's motion. In the closed-loop structure it works as a steering signal corrector which corrects on-line (by two Kalman regulators) the steering system angle signal. The set-point signals, as well as regulators' algorithms are based on a simple reference model (simplified "bicycle model"). In simulation, the virtual object of control – the model of medium-duty truck is very detailed (MBS-type, 3D, nonlinear). This model had been verified experimentally.
Due to the complexity of the vehicle motion model, a sensitivity analysis must be based on comparing results obtained from the simulation with nominal and changed models. In order to objectify the analysis, special integral indexes have been introduced. They use the signals from nominal and changed models. The results of simulation show that the proposed concept of the automatic control is good.
The sensitivity study focuses on the variation of parameters that appear to be crucial for the correct operation of the control system. Bearing in mind the experience of drivers and researchers, difficult situations (slippery road, vehicle unloaded, high speed), as well as measurement errors are taken into account in the simulation investigations.
The presented method of automatic control can be an attractive proposition for designers and researchers of active steering systems which enhance active safety of vehicles. The subject of the work is directly related to the subject of the session Enhancing Safety with Connected and Automated Vehicles.

INTRODUCTION

Driver assistance mechatronic systems are standard features of modern cars. This is particularly true of systems that use braking systems (ABS, ESC, etc.). Mechatronic systems directly related to steering mechanisms are very limited, as yet. They apply mainly to support the driver's effort (servo-type systems), and to stabilize the vehicle's trajectory (active steering systems, 4WS systems), in which powering and gearing are speed dependent. Full automation of driving includes, as of now, only the parking manoeuvre (Parc Assist System), which is implemented at a very low speed - at quasi-static conditions. Full automation of road manoeuvres at high speeds (when the car should be treated as a dynamical system) remains difficult and is still open. Automatic control of lane change is a key for automation more complex manoeuvres, eg. avoiding, overtaking etc.

The subject of lane change automation has been presented in many papers (Bevan et al. 2010, Gao et al. 2010, Moshchuk et al. 2013, Park et al. 2009, Shiller and Sundar 1996). These publications refer to a concept of automatic control including automatic determination of a desired path of travel, and then automatic realization of an assigned trajectory as a problem of tracing and control (regulation).

Within the authors' research project, extensive analytic and simulation studies have been undertaken on application of an active EPS-type steering system in automatic driving of a car (a lorry of medium load capacity equipped with typical elements of the ESC system and obstacle detectors, as well as road monitoring systems) in traffic situations threatening an accident because of a suddenly appearing obstacle. The authorial conception of automatic control of the lane change process has been based on the optimal control theory and a very simple reference model (single-mass, 2D, linear) describing the most important dynamic properties of the vehicle. The controller's model has been tested virtually by simulation investigations with using very detail mathematical model (multi-body, 3D, non-linear) of the vehicle. Simulation investigations enabled testing of control system algorithms for many sets of parameters describing vehicle and road properties. The concept of automatic control system, and many results of simulation tests concerning various vehicle features, and road conditions have been shown in several authors' papers (Gidlewski and Żardecki 2015 a, b, Gidlewski and Żardecki 2016 a, b, Gidlewski et al. 2016).

This paper presents unpublished results of the simulation investigations. They are focused on the sensitivity of the controller due to steering system inertia parameters neglected in the synthesis of controller's algorithms.

CONTROLLING OF LANE CHANGE PROCESS

The lane change process refers to two variables – the lateral displacement of the centre of mass and the angular position of the car body in relation to the trajectory of the centre of mass. According to drivers' experiences as well as to the control theory the steering input signal should have the "bang-bang" form and the control process can be divided into two phases (Fig.1):

Phase 1 – transposition (trajectory shift)

Phase 2 – stabilization (angular stabilization).

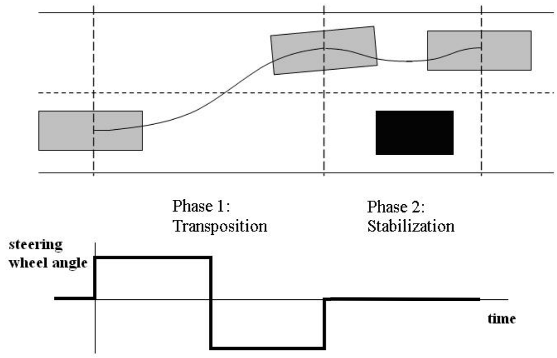

Figure 1. The concept of time decomposition of lane change control and bang-bang type steering

Accordingly, this two-phase control process can be realized in one switchable control system (Fig. 2).

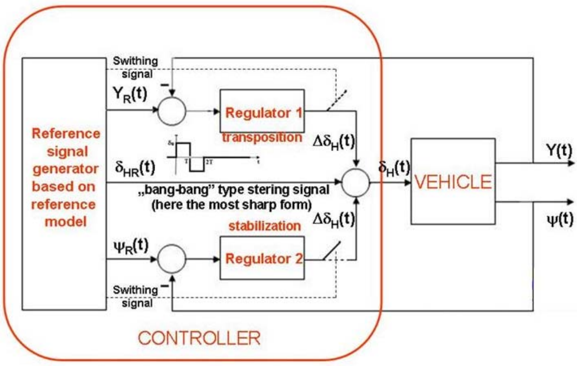

Figure 2. Block diagram of the automatic control system

The lane change controller has a complex structure. Its reference signal generator provides three signals $\delta_{HR}(t)$ (bang-bang type course of steering system angle), $Y_R(t)$, $\psi_R(t)$ (courses of linear and angular vehicle position computed for $\delta_{HR}(t)$ signal) describing the lane change maneuver desired process according to a simple reference model of vehicle motion. The signals $Y_R(t)$, $\psi_R(t)$ are set-point signals for two regulators which correct in sequence the real steering angle signal $\delta_H(t)$ to minimize errors between measured and desired courses of variables. The generated signals, and regulators' algorithms are based on a simple reference model (simplified "bicycle model").

Note, that the "bicycle model" has been used in many papers referring to a car lateral dynamics and car steering. This model defined in local coordinates (x, y) requires only several variables and parameters (fig. 3):

- t – time (t = 0 denotes the moment of starting control),
- $\delta(t)$ – the course of steer angle of front wheels,
- $\psi(t)$ – the course of yaw angle, meaning yaw of the vehicle from the roadway axis,
- $\Omega(t)$ – the course of yaw (angular) velocity of the vehicle ($\Omega(t) = \dot{\psi}(t)$),
- U(t) – the course of linear lateral velocity of the vehicle in a local coordinate system,
- V – linear longitudinal velocity of the vehicle (constant) in a local coordinate system,
- X(t), Y(t) – the courses of position of vehicle's centre of mass in a global coordinate system,
- m – mass of the vehicle,
- J – moment of inertia of the vehicle in relation to the vertical axis in the point of the centre of mass,
- a, b – distances from the front and rear wheel axis of the vehicle, respectively, to the project of the point of centre of mass,
- k_A, k_B – cornering stiffness for the centre of the front and rear wheel axis, respectively.

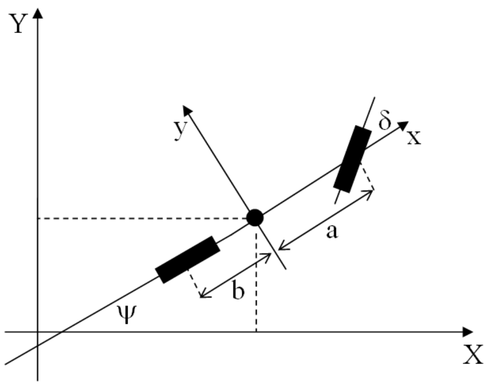

Figure 3. The concept of the bicycle model of car

Well known equations of motion of the "bicycle model" defined in local coordinates (x, y) are linear, but calculation of vehicle trajectory in global coordinates (X, Y) requires additional non-linear trigonometric formulas. For small angles these formulas can be linearized and then the model of car lateral dynamics describing vehicle's trajectory in global coordinates can be presented with using standard Laplace transfer functions. In such equivalent transmittance form of the model its "black box" signals are: $\delta(t)$ – input signal, Y(t) and $\psi(t)$ – output signals. Neglecting steering system dynamics (inertia, damping, resilience) and non-linearities

$$\delta(t) = p\,\delta_H(t), \qquad \delta_R(t) = p\,\delta_{HR}(t),$$

where p – gain coefficient of the steering system.

Description of the mathematical model by two transfer functions $G_{Y\delta}(s)$, $G_{\psi\delta}(s)$ enables detail theoretical analysis of vehicle motion for different courses $\delta(t)$ and then synthesis of reference signals $\delta_R(t)$ (bang-bang signal as combinations of Heaviside functions), $Y_R(t)$ and $\psi_R(t)$. After reductions the transfer functions $G_{Y\delta}(s)$, $G_{\psi\delta}(s)$ receive simple forms:

$$G_{Y\delta}(s) \approx \frac{G_{\Omega\delta 0}V}{s^2} \qquad G_{\psi\delta}(s) \approx \frac{G_{\Omega\delta 0}}{s}$$

where

$$G_{\Omega\delta 0} = \frac{k_A k_B (a+b)V}{k_A k_B (a+b)^2 - mV^2(k_A a - k_B b)}$$

Such transfer functions are sufficient for analytical synthesis of regulators' algorithms with using optimal control systems rules and Kalman's theorems. Final forms of these algorithms are like standard PD regulators, with parameters directly relative to $G_{\Omega\delta 0}$ (that is dependent of the "bicycle model" data). Details of this mathematical description, as well as theoretical validation of the principles of the control system conception have been presented with details in authors' papers (Gidlewski and Żardecki 2015 a).

Of course, the theoretical synthesis of the controller algorithms which exploit only simple mathematical models is not sufficient for validation. The theoretical analysis be supported by extensive simulation investigations with using detail model of the steered object.

SIMULATION STUDIES

As a virtual object of control an "accurate" model of motion of the medium-duty truck STAR 1142 (fig. 4) driven on a straight even road has been used. This mathematical model, and its simulation code were experimentally verified with using results of many road and stand open loop tests.

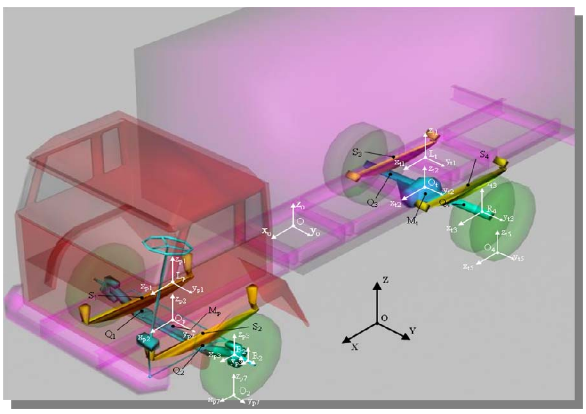

Figure 4. The concept of the physical vehicle's model

The model has 26 degrees of freedom, and requires about 200 parameters. Wheel-road interactions are given by nonlinear Dugoff-Francher-Segel formulas which ensure description of the vehicle motion on many different surfaces, also very wet or icy (important for wheels' slip). Nonlinear equations of motion were derived with using Boltzmann-Hamel method of modelling non-holonomic systems. They have been supplemented by algebraic constrains equations.

Correctness of the assumed concept of control and correctness of regulators operation has been tested in simulation studies consisting in avoidance of a suddenly appearing obstacle (single lane change) on the possibly shortest way (fig. 5).

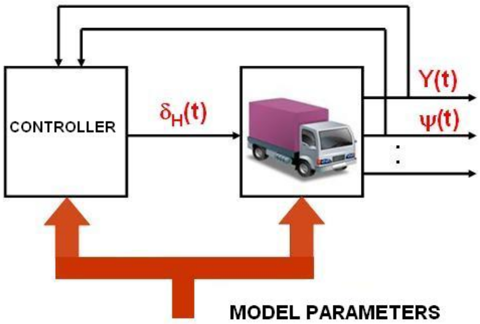

Figure 5. Block diagram visualizing simulation tests of the control system

The tests carried out to assess controller's sensitivity to various possible model inaccuracies are performed in accordance with the schematic diagram shown in fig. 6. In such tests, two simulations are made for each case: the one based on the nominal (initial) model and the another based on the model modified by detuning its parameters, changing non-linear characteristics or adding some disturbances. Based on those simulation results, numerical indexes W_X (eg. W_Y , W_ψ) as relative sensitivity measures give us additional information about of controller's sensitivity .

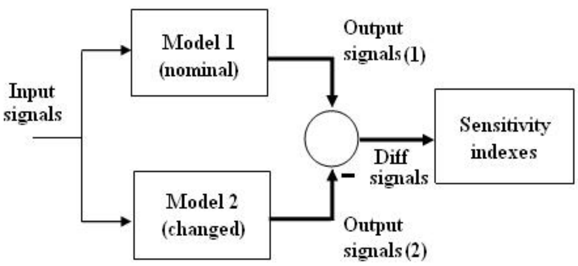

Figure 6. Block diagram of sensitivity analysis based on simulation tests and numerical indexes Wx

$$Wx = 100\frac{\int_0^{\tau}(x_1(t)-x_2(t))^2\,dt}{\int_0^{\tau}(x_1(t))^2\,dt}$$

Due to the complexity of the truck motion model, a sensitivity analysis should answer the question: How important are inertia properties of the steering system servomechanism. First studies of this problem have been reported in (Gidlewski at al. 2017) with using the first order description of inertia effects by an additional standard transfer function block (with single time constant T), which modifies the steering signal $\delta_H(t)$ to the more smooth form $\delta_{H*}(t)$. In that investigation the nominal model worked with T = 0, while the changed model worked with T > 0. For given T, the sensitivity indexes, especially $W_{\delta H*}$, W_Y, W_ψ, expressed rather small significance of this time constant. Therefore sensitivity analysis was enlarged and a second order transfer function has been used for increase inertia effects. This will be reported below.

EXAMPLES OF SIMULATION BASED SENSITIVITY STUDIES

Here, we analyse effects of time constant T of a 1st as well as 2nd order transfer function block. For such virtual block the signals $\delta_H(t)$ and $\delta_{H*}(t)$ are input and output signals respectively. In this case the modified steering signal $\delta_{H*}(t)$ is smooth indeed (fig. 7), especially when inertia effects are modelled with 2nd order transmittance block.

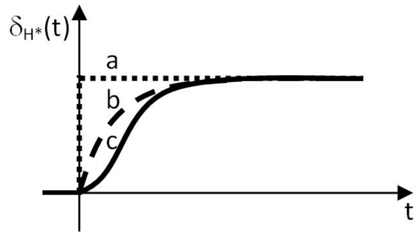

Figure 7. Effect of the time constant T in the output signal when the input signal is steep – type. (a: T = 0, b: T > 0 in 1st order block, c: T > 0 in 2nd order block)

Simulation based sensitivity investigations of the lane change control process have been realized for different values o the time constant T (in 1st and 2nd order transmittance block) as well as repeated for different vehicle and road operating parameters. In this studies the steering system model working without time constant has been treated as the nominal model (1). Variations of model parameters concerned of: vehicle's velocity V, wheel-road friction coefficient μ and degree of vehicle loading (note, that the loading variation causes the changes of many parameters, eg. m, J, k_A, k_B, a, b – in the "bicycle model"). The simulations have been done also for "difficult" conditions of the car motion (eg. unloaded vehicle driven on a slippery road with a high speed). The research contained a lot of sets of data.

In this paper, example results are presented (fig. 8-10, tab. 1). Here, $T \subset \{0, 0.1\}$, $V \subset \{60, 70, 80\}$km/h, $\mu \subset \{0.2, 0.3, 0.4\}$. In these studies the truck was full loaded. For better understanding an importance of the regulators, the simulations have been repeated for the system working with and without regulators.

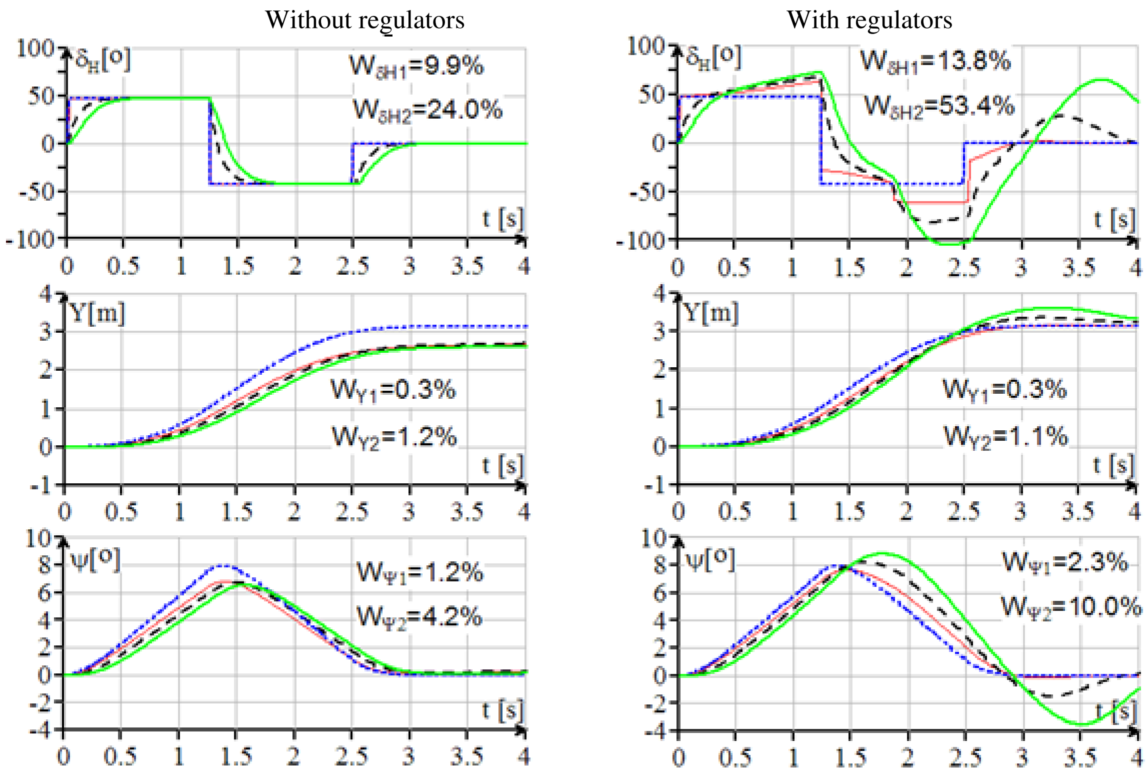

Figure 8. Steering system inertia effects in control process (here V = 60 km/h, μ = 0.2, full loaded vehicle) Point blue line- for reference signals, red solid line – when T = 0 s, dash black lines - when T = 0.1 s in 1[st] order block, green solid line when T = 0.1 s in 2[nd] order block.

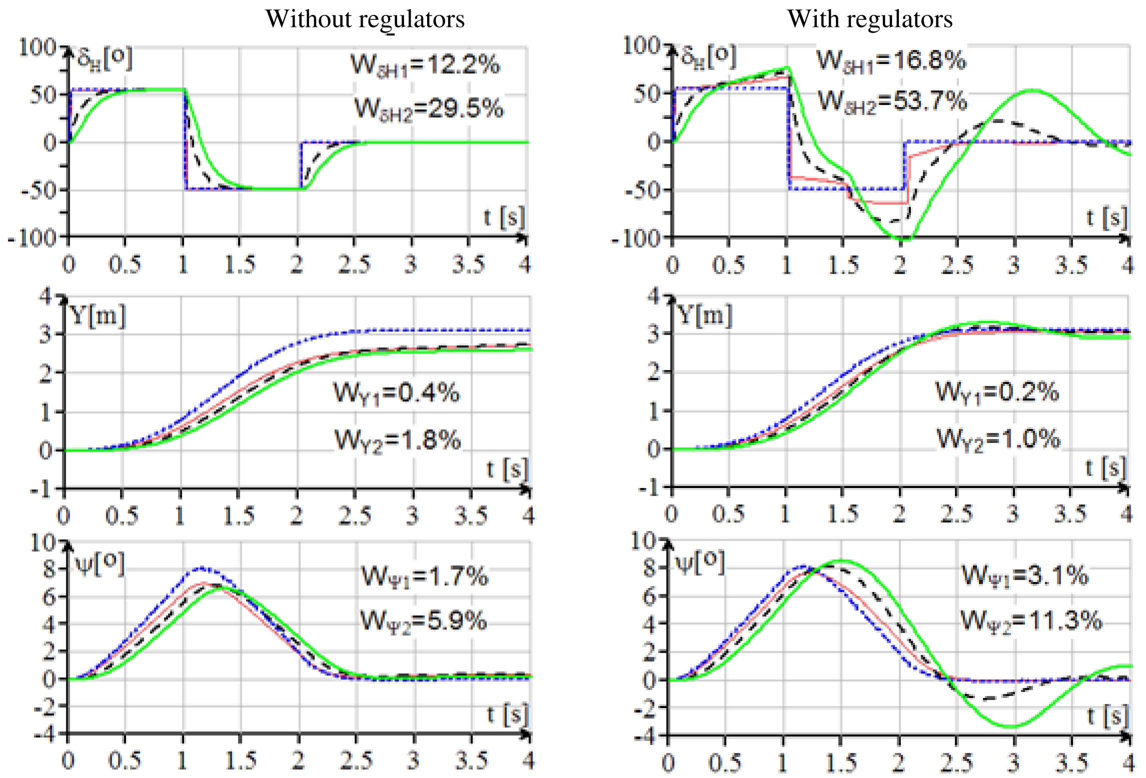

Figure 9. Steering system inertia effects in control process (here V = 70 km/h, μ = 0.3, full loaded vehicle) Point blue line- for reference signals, red solid line – when T = 0 s, dash black lines - when T = 0.1 s in 1[st] order block, green solid line when T = 0.1 s in 2[nd] order block.

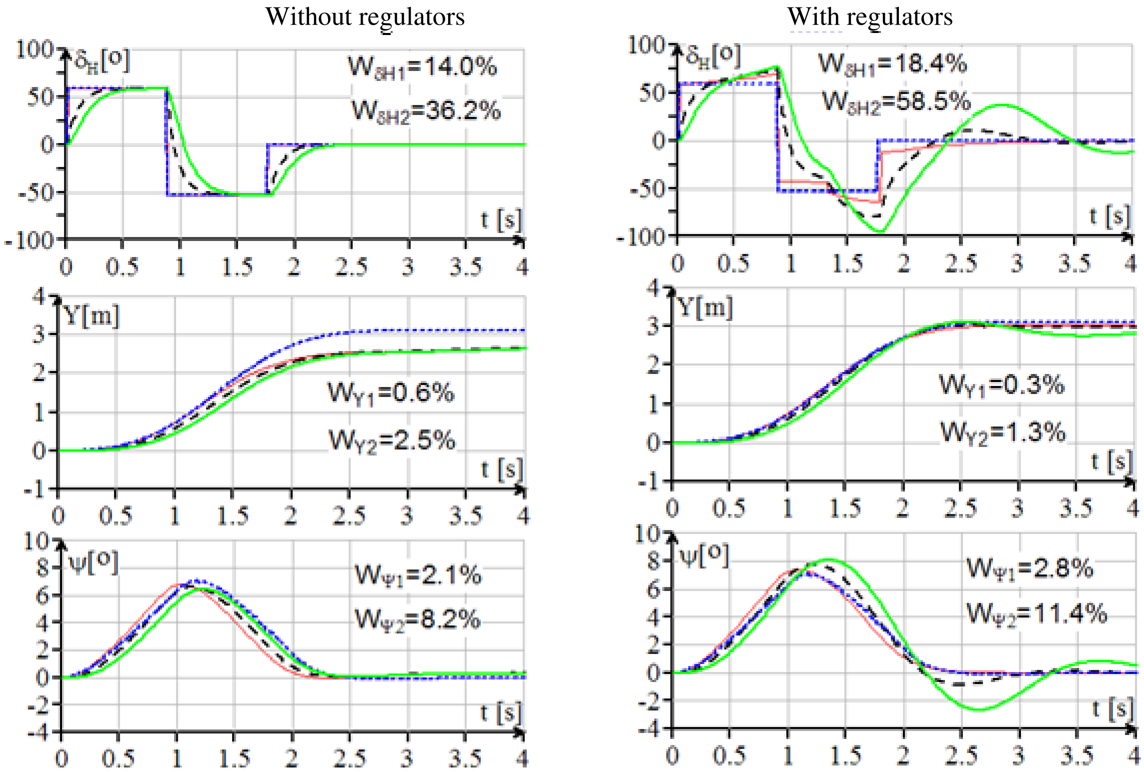

Figure 10. Steering system inertia effects in control process (here V = 80 km/h, μ = 0.4, full loaded vehicle) Point blue line- for reference signals, red solid line – when T = 0 s, dash black lines - when T = 0.1 s in 1st order block, green solid line when T = 0.1 s in 2nd order block.

Table 1. Sensitivity indexes when the controller is equipped with the regulators.

		μ = 0.2		μ = 0.3		μ = 0.4	
		1st order block	2nd order block	1st order block	2nd order block	1st order block	2nd order block
V = 16.67 m/s (60 km/h)	$W_{\delta H}$* W_Y W_ψ	13.8% 0.3% 2.3%	53.4% 1.1% 10.0%	14.6% 0.2% 2.6%	54.1% 1.1% 11.3%	18.2% 0.3% 3.0%	60.0% 1.2% 12.3%
V = 19.44 m/s (70 km/h)	$W_{\delta H}$* W_Y W_ψ	14.2% 0.3% 2.5%	50.9% 1.0% 9.6%	16.8% 0.2% 3.1%	53.7% 1.0% 11.3%	18.4% 0.3% 2.9%	59.5% 1.3% 11.9%
V = 22.22 m/s (80 km/h)	$W_{\delta H}$* W_Y W_ψ	15.3% 0.2% 2.6%	54.8% 1.0% 10.2%	16.8% 0.2% 3.0%	56.2% 1.0% 11.9%	18.4% 0.3% 2.8%	58.5% 1.3% 11.4%

The results of simulations and corresponding indexes' values demonstrate that the influence of the time constant is not especially significant for lane change control process, even the steering signal is smooth. Sensitivity of the system is bigger for 2nd order than for 1st order transfer function block. Sensitivity of angular position of the car is greater than sensitivity of linear transposition. Of course, the system's sensitivity increases a little for more difficult conditions of motion (big V, small μ). Note that when the controller has not any regulators the course of the linear transposition signal increase systematically (no steady state)! This confirm regulators' signification.

Rather small sensitivity of the lane change control process on parameters' variations is probably the result of feedbacks between the object and its controller, when the control system works with regulators.

CONCLUSIONS AND CLOSING REMARKS

We could notice that the lane change automatic controller (equipped with the regulators) characterizes rather small sensitivity of on variations of object's and its reference model's parameters, also on neglecting inertia effect properties in the reference model.

The results of the simulations have shown that in all tests the lane change manoeuvre was realized correctly, even the steering system worked with second order inertia block having small time constant and conditions of vehicle motion were changed in a broad range.

The proposed method of automatic control of the lane change manoeuvre may be attractive for designers and researchers of mechatronic active steering systems that enhance active safety of cars (also lorries and trucks).

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